Int J Life Cycle Assess (2010) 15:621–634
DOI 10.1007/s11367-010-0174-5

LIFE CYCLE MANAGEMENT

Metals recycling maps and allocation procedures in life cycle assessment

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Received: 27 January 2010 / Accepted: 24 February 2010 / Published online: 19 May 2010

Abstract
Goal, scope, and background The aim of this work is to present guidance on the application of ISO 14044 to allocation procedures for metal recycling. As such, graphical patterns of metal recycling and generic “rules” for metal recycling maps are presented. The results are intended to be useful in assessing and validating the suitability of allocation procedures for metal recycling in the context of life cycle assessment (LCA) and assist in the understanding of metals flow patterns in product systems. LCA uses a product-focus; therefore, the perspective here is on recycling metals in post-consumer products. The discussions, analysis, and illustrations in this paper emphasize old (post-consumer) scrap and do not detail flows of new (post-manufacturing, pre-consumer) or prompt (internal) scrap. The work included participation and review from International Council on Mining and Metals, the Nickel Institute, the International Copper Association, the International Zinc Association, worldsteel (formerly International Iron and Steel Institute), and the International Aluminium Institute.
Methods A survey of generic metal flows was conducted for three major non-ferrous metals—nickel, copper, and zinc. Based on the results of this survey, four metal recycling map models were developed. Implications of these recycling maps for LCA were then considered, and parameters necessary to model metal recycling were presented. Relationships of inherent properties and recycling loops are provided and connected to the allocation procedures in the context of LCA.
Results and discussion Four metals recycling map models were generated based on a survey and analysis of current metals flow analysis. The utility of the recycling maps is to serve the basis of a structured approach to recycling allocation in life cycle assessment and leveraging the efforts of harmonized recycling metrics.
Conclusions A consensus on mapping metals is important in order to achieve an accurate understanding and measurement of metals recycling. To this end, consensus mapping presentation of a general allocation approach and identification of harmonized metrics were achieved among representatives of ferrous and non-ferrous metals groups.
Perspectives For the future, allocation factors based on sound empirical data needs to be developed. Those metrics will empower the various stakeholders—industry, policy makers, non-governmental organizations, and academics to make appropriate decisions based on agreed scientific bases.

Keywords Allocation · Life Cycle Assessment (LCA) · Metals · Recycling

Responsible editor: Gerald Rebitzer

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1 Introduction

The metals industry is working towards the establishment of an accurate understanding and measurement of metals recycling. Until recently, there has been neither a consistent perspective nor a set of recycling indicators available for the metals industry as a whole (Campbell 1996; Desrochers 2000; Ekvall 2000; Erol and Thoming 2005; Geiser 2001; Georgiadis and Besiou 2008; Gleich et al. 2006; Henstock 1996; Kirchain and Cosquer 2007; Pelletiere 2001; Ruhrber 2006; Steinhilper and Hieber 2001; Gordon et al. 2006; Graedel et al. 2004, 2005; Harper et al. 2006; Verhoef et al. 2008). As a consequence, a wide variety of different metal recycling rates with different meanings and implications have been published. This has resulted in some confusion and lack of understanding of the efficiency with which metals are recycled.

The recycling performance of metal-bearing products can be measured and demonstrated in a variety of ways—depending on, among others, objectives, scope, data availability, and target audience. Performance measures can be used:

- to demonstrate the process efficiency of collection and recovery activities
- to track historical, current and future secondary raw material availability to a sector or region
- to demonstrate status and trends in recycling performance of a region, sector, or company
- to calculate statistical ratios to show the extent to which materials in products are recycled/recyclable and/or to highlight the amount of recycled metal which is contained in products or sectors
- to identify areas in which waste prevention and end-of-life management can be optimized and recycling increased
- in conjunction with other environmental indicators (such as energy efficiency or emissions) to assess benefits and potential impacts associated with the life cycle of products or processes
- to measure benefits and impacts of current or future recycling policy measures and technologies

The metals industry as a whole supports and promotes the characterization and modeling of recycling of metal-containing products in a way that:

- Aids assessment of the overall life cycle of products and understanding of materials
- Supports the management of the life cycle of products and stewardship of materials
- Encourages good environmental practices
- Is consistent with scientific knowledge and technical practices
- Reflects economic realities without creating market distortions that impede objectives of sustainable development

The aim of this work is to present guidance on the application of ISO 14044 (2006) to allocation procedures for metal recycling. As such, graphical patterns of metal recycling and generic "rules" for metal recycling maps are presented. The results are intended to be useful in assessing and validating the suitability of allocation procedures for metal recycling in the context of life cycle assessment (LCA) and assist in the understanding the complexity of flows of metals in product systems.

2 Methods

The International Council for Mining and Metals (ICMM) engaged a select group of LCA practitioners familiar with metal production and metal lifecycles. A survey of generic metal flows was conducted for three major non-ferrous metals—nickel, copper, and zinc—utilizing information from the respective commodity associations. This information consisted of material flow diagrams, materials flow data, life-cycle inventory profiles, and other quantitative data on industry practices. Some of the information was associated with specific product types (e.g., copper tube for heating and cooling equipment). Using the results collected from the survey, and based on existing consideration of materials recycling loops by Stewart et al. (2004), graphical metal recycling map models were developed for the three metals. These maps focus on the flow of metal through product systems and are intended to inform LCA practitioners on the patterns and consequences of material use and end-of-life. The participating metal associations provided review of the graphical patterns. Subsequent analysis revealed was undertaken to discern possible generic patterns and types to assist in the understanding typical patterns of metals flows in product systems.

Implications of these recycling maps for LCA were considered and two parameters were defined as necessary to model metal recycling. The definitions of these parameters were evaluated in comparison to guidelines provided in the ISO 14040 series on LCA and in comparison to approaches developed separately by the worldsteel and the International Aluminium Institute.

The work included participation and review from the ICMM, the Nickel Institute, the International Copper Association, the International Zinc Association, the International Iron and Steel Institute, and the International Aluminium Institute.

2.1 Background

Metal recycling has been a fact of society and economics for thousands of years. Young et al. (2001) suggested that sustainable materials management approaches, including

recycling, should reflect basic structural characteristics of materials: Metals are indestructible atoms and unique materials because of their atomic bonding, and so are distinguished from molecular based materials, like plastics, and fiber materials, i.e., wood. Metal that has been mined from the earth and refined into a usable form is theoretically infinitely reusable with burden-free energy as metal, whether as pure metal or (more commonly) as an alloy mix of one or more metallic elements. The major limitation of prolonged metal use and reuse is our ability to effectively recover and reconcentrate discarded material—that is to recycle.

While metallurgical recycling processes are well established for steel, aluminum, and base metals, the economic viability depends on various factors such as the volume of metals accessible, regulations, cost, and reactivity of the metals. The ability to sort and refined metals is variable.

The potential benefits of metal recycling are widely accepted. An advantage of recycling is the resource conservation: if a metal is recycled, then that material remains available in the economy for reuse. Recycled metal substitutes or displaces the necessity to mine. Consequently, the primary production processes required digging, crushing, smelt, reacting, refining, or otherwise metallurgically extracting and refining the metal will be offset. A second consideration is the issue of waste avoidance, because recycled material is diverted from potential landfill or other disposal routes.

2.2 Recycled content versus an end-of-life recycling approach

Two approaches for assessing the benefits of recycling are commonly used: “recycled content” approach and the “end-of-life” recycling approach. Their perspectives and purposes differ and can yield opposing courses of action to improved efficiencies and reduced environmental burden (Atherton 2007).

The recycled content approach is commonly used in environmental labeling, and is typically symbolized by the Mobius loop applied to a product as described in ISO 14021 (1999) and ISO 7000 (2004). The intended aim according to ISO 14049 (2000) of this approach is to stimulate environmental improvements and increase opportunities for consumers to make informed choices by diverting material from the waste stream. The recycled content approach focuses on material feedstock sourcing, providing an incentive towards waste diversion. This perspective aims to promote a market for recycled materials that is otherwise limited, uneconomic, or immature. The recycled content approach is most useful as a metric for materials that would otherwise be incinerated or landfilled as waste. This is not the case for the majority of metals, where the recycled metal market is fairly mature, and the economic basis for recycling metals continues to increase with rising energy costs and sensitivity to the risks associated with mining. Unfortunately, application of the recycled content approach may create market distortions and environmental inefficiencies. For metals, where there is a limited supply of recycled feedstock, market stimulation is ineffective and may result in inefficient processing and unnecessary transportation.

In the Leadership in Energy and Environmental Design (LEED) Green Building Rating System™ points are given “to increase the demand for building products that incorporated recycled content materials, thereby reducing impacts resulting from extraction and processing virgin materials” (USGBC 2008). Under that context, there is the implicit judgement that the first user of a material is accountable for the primary production. After the use phase, the material is “burden free” because the impact of the primary production has been “paid.” The subsequent user is accountable only on the impact of recycling which is considered to be smaller than the primary production.

The end-of-life recycling approach follows the guidance of ISO 14040 2006 and ISO 14044 2006. The end-of-life recycling approach focuses on considering the whole lifecycle of the product including its end disposition. This method is based on the premise that materials not recycled need to be replaced by primary materials. By designing for recyclability, that is, giving an incentive to making materials available after use, market efficiencies and environmentally preferable solutions will prevail, and market distortions and environmental inefficiencies will be avoided (Atherton 2007). This end-of-life approach is also supported by ISO 14025 (2006), whereby Type III environmental declarations are based on complete LCA while environmental labeling is based on single attribute.

The metals industry strongly supports the end-of-life recycling approach over the recycled content approach for the purposes of environmental modeling, decision-making, and policy discussions involving recycling of metals. The weakness of the recycled content approach arises from the fact that a simple account of the history of a material provides no assessment of actual environmental performance. The recycled content metric does little to guide decision-makers wishing to better manage metals and metal-containing products. Moreover, and of particular concern, pursuit of recycled content may generate market distortions and result in environmental and economic inefficiencies (Atherton 2007).

In contrast, the end-of-life recycling approach promotes design for recyclability and encourages manufacturers, policy-makers, and other decision-makers to evaluate real performance and improve the design and management of products, including their disposal and recycling. A more

comprehensive presentation of the merits of an end-of-life approach can be found in Atherton (2007).

2.3 Closed-loop and open-loop allocation for end-of-life recycling

There are two general concepts that need to be understood in order to characterize metals recycling. The first concept, closed-loop versus open-loop recycling, relates to capturing the inherent resilient quality (properties in ISO language) of metals in the most appropriate manner. The second concept, a "recycled content" versus an "end-of-life" modeling approach, is important to ensure the actual and overall environmental impact of a product can be accurately determined.

Frequently, when discussing the recycling of any material, a distinction is made between closed-loop recycling and open-loop recycling. Closed-loop recycling occurs when a material associated with a product is used again in the same product at the same level of material quality, that is, the inherent properties are maintained by closed-loop recycling. The approach focuses on the properties of the material rather than on the product. The goal is to optimize the utility of the material (e.g., a unit of metal or alloy) throughout multiple product uses. For example, post-consumer aluminum can scraps are reclaimed and used to make new aluminum cans.

Closed-loop recycling also applies when a material is recycled in another product system when its inherent properties are maintained. The basic question is: what are the benefits of recycling one unit of scrap. If the answer can be expressed in term of displacing the primary production, then we are justified to apply a closed loop allocation procedure (ISO 14044 2006; ISO 14049 2000). Nickel is used to make aircraft turbines. After the use phase, the scrap turbines can be blended with carbon steel scrap to make stainless steel. In that case, from the point of view of nickel, recycling the turbines displaced the need to produce primary nickel.

Open-loop recycling occurs when a material associated with a product is recycled to a different product system and the material has undergone a change in its inherent properties (ISO 14049 2000). An example is the recycling of tin can. Tin is used as a coating inside steel cans for corrosion protection purpose. When the steel scrap is melted, tin enters in solution. On solidification, tin is still present in the steel, but it does not perform any function in regard to corrosion protection. As we are not willing to add primary tin to the steel, tin can be considered a tramp element, i.e., an unimportant or undesirable to the quality of the steel. We thus have an open-loop recycling of tin, and the tin is effectively lost in the system.

3 Results

3.1 Metals mapping general frameworks

In order to appropriately assess the performance of metals recycling, a basis for the metrics need to be determined and agreed upon by all the stakeholders involved in the life cycle of metal-containing products. Results of the recycling maps exercise resulted in four recycling types being identified:

Type 1: Closed metal loop
Type 2: Closed alloy loop
Type 3: Transfer to other metal pool
Type 4: Transfer to and recovery from other metal pool

These four recycling types represent generic patterns apparent from the flows and processing of metals. A metal map graphically depicts the pools and flows of metal across an economy. The metal maps focus on following a metal from its source, to production, use, and recycling. Prompt scrap (scrap caused by manufactures of metal products) and obsolete scrap (scrap caused by consumers of metal products) recycling loops are included in the mapping, with emphasis on obsolete scrap. Home scrap (scrap caused by foundries and mills) recycling is not illustrated by the mapping, as it occurs within the primary production unit processes. The maps also illustrate metals lost in disposal or by emissions. Metal volumes that are lost in this way would need to be replaced by virgin metal production.

3.2 Definitions of map elements

Recycling is a series of activities rather than a specific flow or process. It includes refining and melting processes that may be combined with primary metal inputs or may be independent. Definitions and approaches to quantifying recycled content can be found in ISO 14040 (2006), ISO 14044 (2006), and ISO 14049 (2000).

The main recycling loops present in typical metal production, use, and end-of-life activities are shown in Fig. 1. Each box represents an activity associated with a metal, and arrows represent metal flows. The maps track a given metal, labeled metal A, and any additional metals for alloying or coating are labeled metal B. Metal B flows are only indicated to help track the recycling process of metal A. Black arrows refer to metal and products moving along the value chain of the metal cycle for metal A, including metal recycling and indication of losses. Flows of recycling from semi-manufacture and manufacturing stages are common but are not illustrated here.

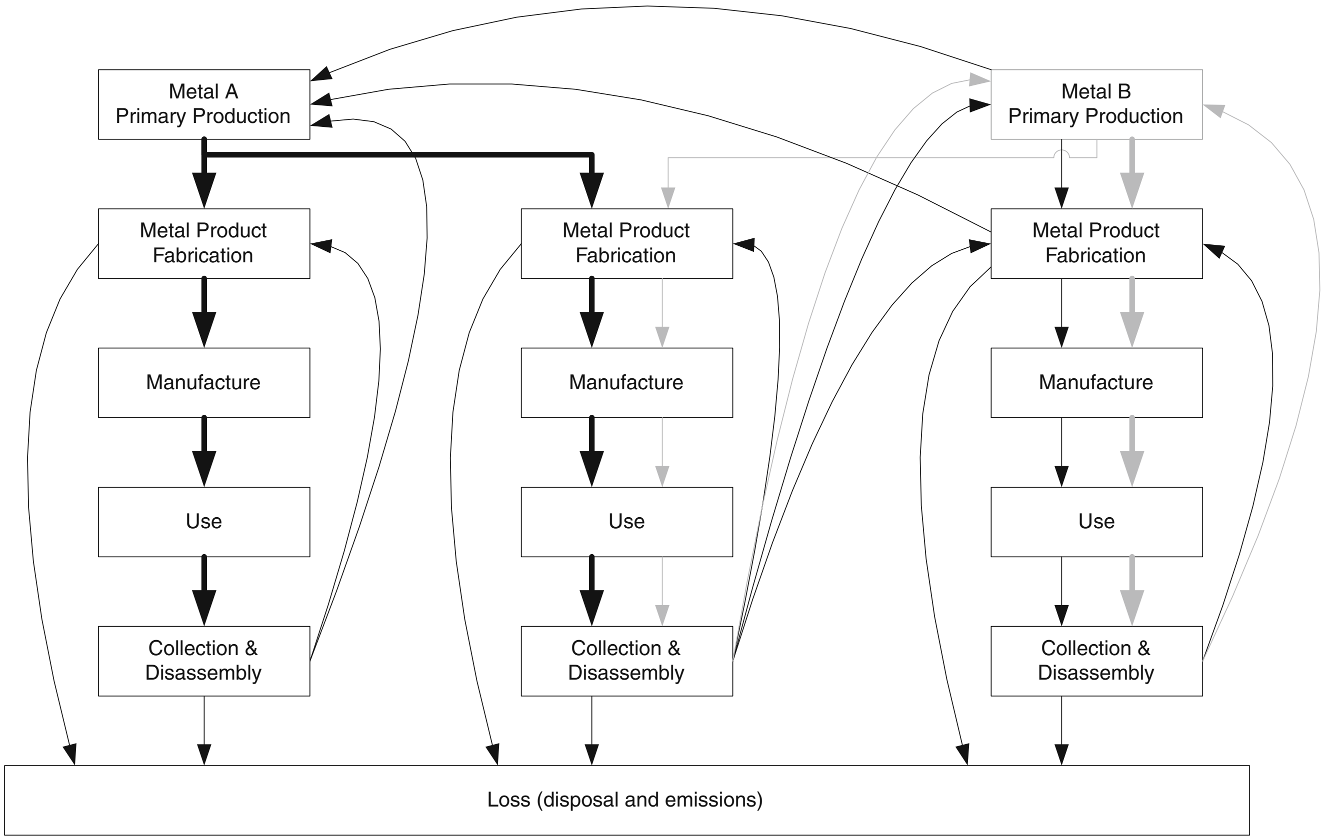


Fig. 1 Typical life cycle activities and flows for metal

3.2.1 Metal primary production

Generic recycling maps distinguish two metal production processes—primary metal production and metal product fabrication. Primary metal production refers to activities beginning with mining and ending at metal commodity level product. This may involve concentrating, reducing, smelting, refining, alloying, and ingot casting. They are the activities that take minerals from the earth and process them to metal.

3.2.2 Metal product fabrication

Metal product fabrication refers to a number of metallurgical processes that include alloy production, composition adjustment, rolling, extrusion, pressing, and other forming activities. The output of metal product fabrication includes metal plate, sheet, tube, long products, wire, extruded cross sections, coated products, etc. The products are produced according to detailed specifications and are the building blocks for fabrication and manufacturing of final products.

Fabricators do not typically distinguish between the source of metal that is used as feed because the metallurgical processing that takes place in metal product fabrication is independent from whether a unit of metal is primary metal or recycled metal.

3.2.3 Manufacture

Manufacture refers to processes that are downstream of metal product fabrication. This includes a multitude of forming, assembly, production, and construction steps. Manufacture output is at the point of finished product ready for retail.

3.2.4 Use

The use phase is where a product provides a function or service. The use phase has a lifespan, which varies greatly, and is determined by product function, durability, and other characteristics. The length of time in use is not represented by the metal maps; however, lifespans can be significant, such as in the case of buildings (50 to +100 years) and automobiles (10 to 15 years). At the end of a product's useful life, it is no longer desired for its intended use and may enter the end-of-life recycling phase.

3.2.5 Collection and disassembly

A certain fraction of end-of-life products will be collected, and the materials that make them up will enter the recycling system. Collection is the first step, including pickup, transportation, and perhaps some preliminary sorting and processing (e.g., shredding, magnetic sorting, eddy-current sorting, sink–float sorting, and delacquering). Collection refers to activities immediately following use, where end-of-life products and/or components are retrieved for disposal or recycling.

For some products, a disassembly step is also required. For example, automobiles are partially dismantled in order to remove large components, valuable materials (catalytic converters), and hazardous items (fluids, batteries, mercury switches). The outputs of the collection and disassembly steps are metal-rich streams that are suitable as inputs to metallurgical processes. Separation is then often also necessary. Many products are characterized by complex systems of components, coatings, and additives. Although a particular product may be primarily of one metal, numerous other metals may also be present, along with other non-metallic materials such as, plastics, ceramics, and wood or organic matter. Separation may be physical or chemical. It may be performed as part of the collection and disassembly operation or may be part of metallurgical processing. The greater the heterogeneity of the waste stream, the greater the challenge of recycling. These metals are recycled into the primary or secondary route, where they are remelted and finally reprocessed in the semi-manufacture process. Some fraction of used products will not be recovered at the collection and disassembly step. The materials in these products find their way to disposal or are otherwise lost.

3.2.6 Losses

The generic recycling maps emphasize only losses occurring during the use and the end-of-life stages. In practice, losses can occur from all processes. Solid residues are generated in the form of dust, slag, waste rock, cuttings, contaminated parts, or disused products; notably, some of these may be further utilized as by-products (e.g., slag used for road aggregate). The four recycling maps are described in detail below.

3.3 Recycling Type 1: closed metal loop

Recycling Type 1 is where one type of metal (here designated metal A, as the metal of interest) is recycled in a closed metal loop (Fig. 2). The general pattern is a cycling of one specific metal back to product manufacture or primary production, not necessarily for the same use, but likely for the same quality of use by the virgin metal. The loop may be closed by the metal product fabricator where it is remelted and re-refined or returned to the primary process stream where it is resmelted or re-refined. In certain cases, the recycled stream is mixed with primary metal during the melting process to ensure property and composition specifications. Even in this simple case, significant losses may occur depending on efficiency of use, collection, disassembly, and metallurgical processing.

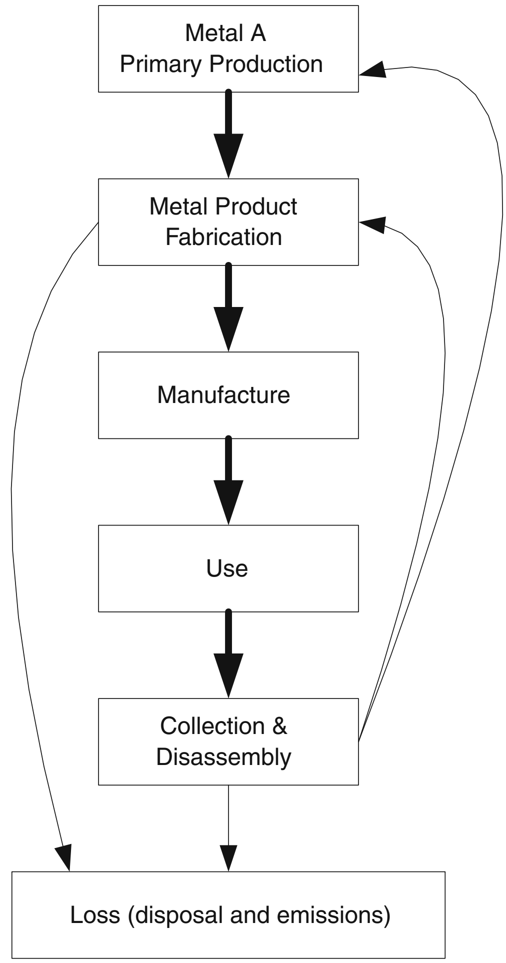


Fig. 2 Recycling Type 1: closed metal loop

3.4 Recycling Type 2: closed alloy loop

Recycling Type 2 describes a situation where two or more metals (described simply as metals A and B, where metal A is the metal of primary interest in the model) are combined in an alloy that forms a distinct metal stock, which is then used and recycled in a closed alloy material loop (Fig. 3). An alloy is a combination of two or more metals that together have desirable properties different to those of the individual components. Metals from various primary or recycled sources are blended to form an alloy pool. At end-of-life of the product, material is recycled back to the metal product fabricator where it is remelted and re-refined.

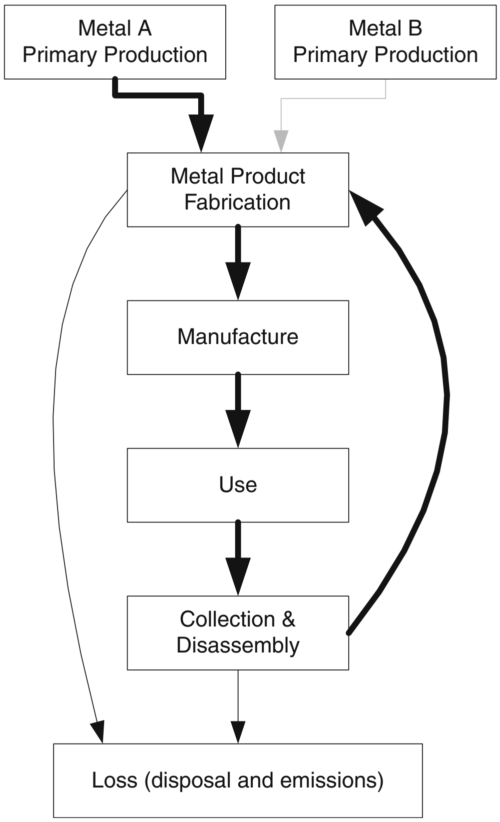


Fig. 3 Recycling Type 2: closed alloy loop

Significant losses can occur depending on the efficiency of collection, disassembly, and metallurgical processing. As with Type 1, economics provide an incentive to collect and recycle specific alloys, depending on availability, ease of separation, logistics, and prices. It is usually more cost-effective and efficient to preserve the material in its alloy form than to try to separate it into constituent metals.

3.5 Recycling Type 3: transfer to other metal pool

Recycling Type 3 represents a pattern where recycling transfers one metal into another metal's pool. This situation occurs when metals A and B are mixed in a product or alloy where the dominant constituent is metal B. For example is if metal A is used as a coating over a base metal B, or metal A is used as an alloying element constituent in metal B. In this scenario, fragments of metal A are not separated from the larger volume of metal B, as shown in Fig. 4. The effect is the same: the original metal A is recycled with and diluted into another metal B, where it becomes part of the other's makeup. At product, end-of-life metal B is the target for recycling. When quantities containing metal B are recycled, metal A is carried along and retained at low concentrations with metal B. When metal B is recycled, metal A becomes diluted into metal B. Engineering specifications allow for degrees of purity or contamination within metals. If the presence of small quantities of metal A in metal B is not detrimental, then it is unnecessary to separate or remove excess metal A from metal B. Once in metal B, metal A's properties are no longer used, but some value is retained by displacing the need for additional units of metal B. In some cases, metal A is detrimental to the metallurgical properties of metal B. Moreover, metal B (and any retained constituent metal A) would continue to be used in the pool for metal B and may be recycled again in the metal B loop. In several cases, metal A is effectively lost when it is reprocessed with metal B.

3.6 Recycling Type 4: transfer to and recovery from other metal pool

Recycling Type 4 follows from Type 3. This is where metal A is subsequently reseparated during the recycling at metal B product fabrication, allowing the original metal A to be recovered and returned in the original metal A pool (Fig. 5). Metal A is ultimately reprocessed to a level of high purity, similar to recycling Type 1. It should also be noted that this pattern is likely where metal A is used as a coating on metal B or where fragments of metal A are not separated from a larger volume of metal B. Collection and disassembly are generally optimized to recycle metal B, not metal A. Consequently, significant losses of metal A may occur at the collection and disassembly or at the metallurgical recycling of metal B.

Simplified comprehensive examples representative of real-world recycling conditions for copper, zinc, and nickel are presented in Figs. 6, 7, and 8. As can be seen by these "simplified" metal maps, the flows of metals in the global economy can be highly complex, making the task of assessing actual recycling rates a challenge (for types 1 to 4, see Table 1).

3.7 Implications for life Cycle Assessment: allocations methods

3.7.1 Towards a unified approach to measuring recycling performance

Metals have a number of important attributes that are significant for sustainable development. They have unique properties that bring high economic value, and as elements, they cannot be destroyed. Once extracted from the lithosphere, their useful life may span several uses or product cycles. However, when compared to other materials such as plastics and wood, metals typically have a greater environmental impact associated with primary production. In order to appropriately compare a specific metal to other materials, we must consider not only the burdens associated with producing the primary metal but also the benefits associated with its

Fig. 4 Recycling Type 3: transfer to other metal pool

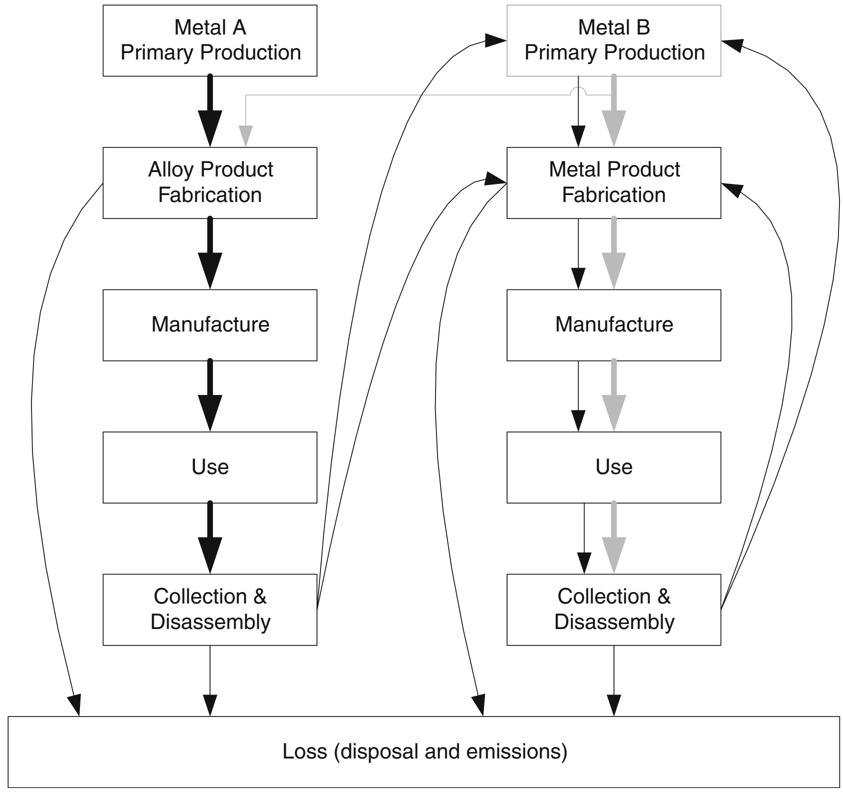
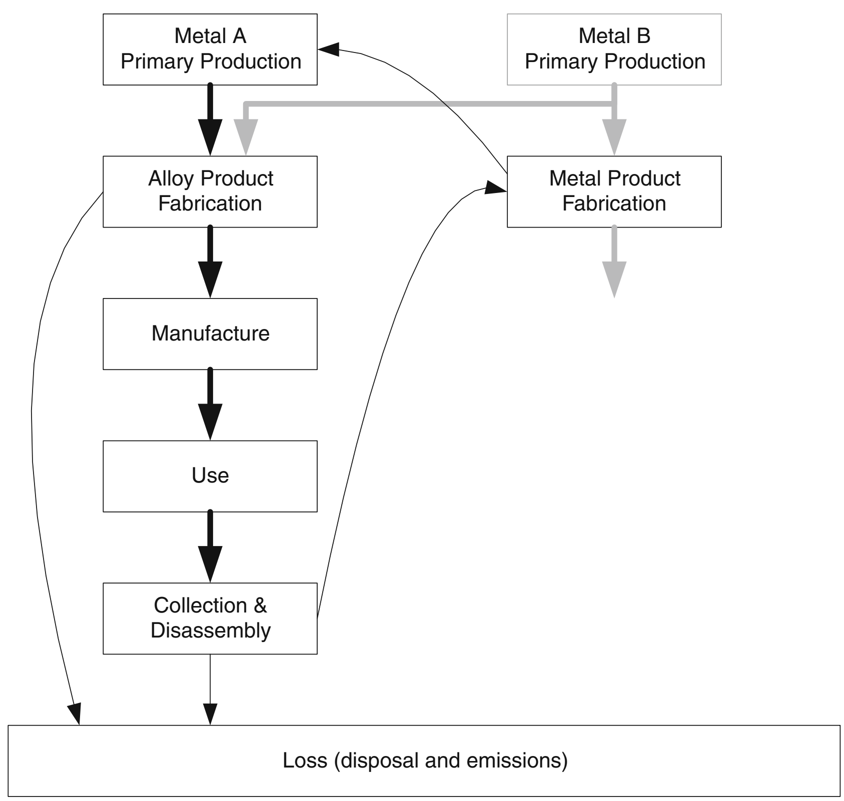


Fig. 5 Recycling Type 4: transfer to and recovery from other metal pool



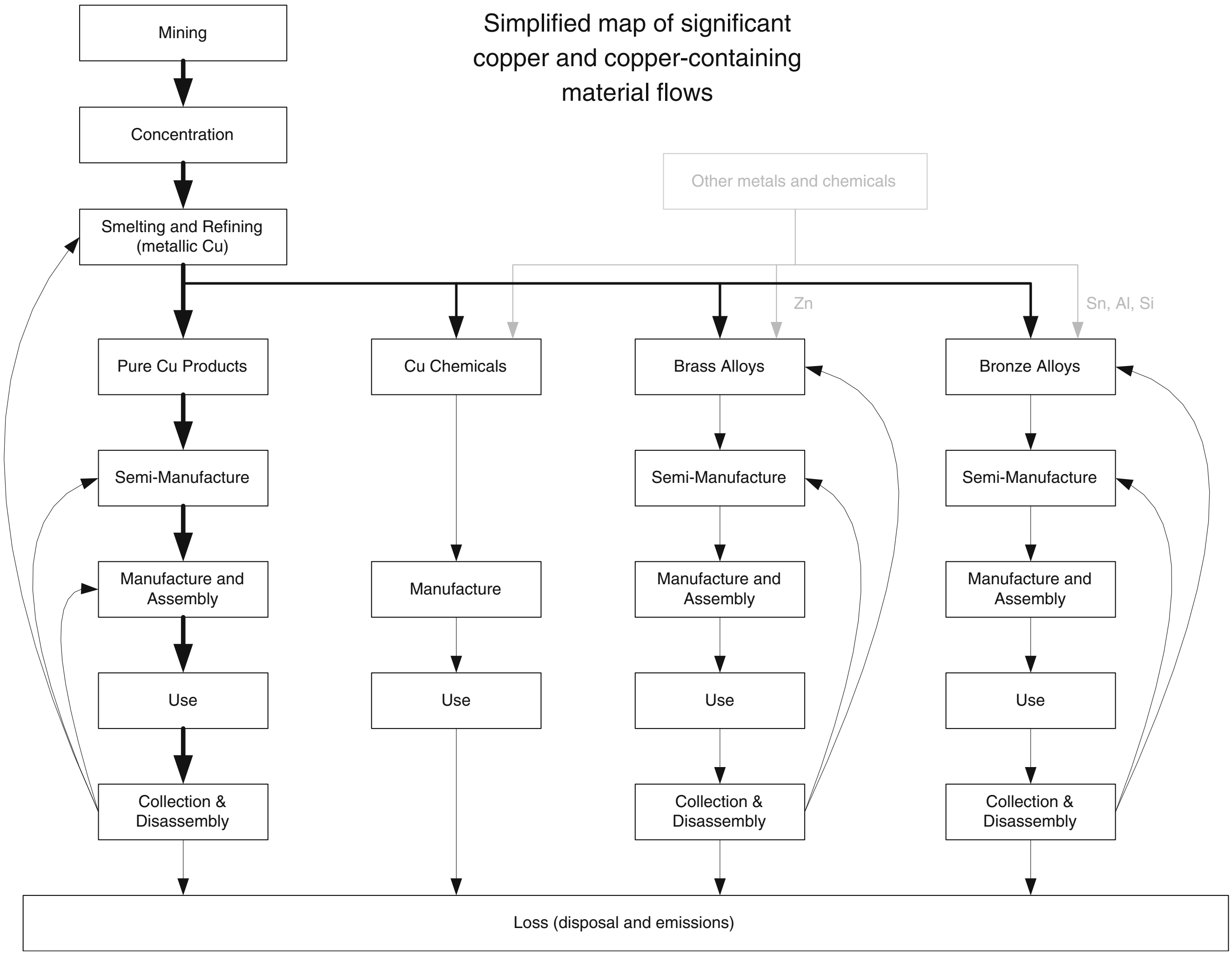


Fig. 6 Copper—recycling map

inherent recyclability. These benefits are most relevant and quantifiable for metals that are in products with clearly identifiable and measurable recycling loops.

One method that takes this real-world perspective into account is environmental LCA. Life cycle assessment is an industry accepted and ISO standardized method for assessing the impact or burden of a product, process, or service over its useful life, from "cradle-to-grave" (ISO 14044 2006; ISO 14049 2000). By taking a life cycle perspective, it is possible to incorporate and communicate the beneficial recycling properties of metals in a manner that enables appropriate comparisons.

3.7.2 Allocation of environmental burden—implications for life cycle assessment

The generic recycling maps introduced above have implications for how metals might be treated in LCA. In order to appropriately allocate environmental burdens in a life cycle assessment study, one must understand both the material properties associated with recycling, that is, the inherent properties of the metal before and after recycling and data describing the quantities of material that loop and flow within recycling loops. If the quality of a material is such that after recycling, the recycled material can offset the production of virgin material, a closed-loop-based calculation of environmental burden can be applied. This approach avoids a qualitative and value-based judgment to allocate burden.

3.7.3 Modeling recycling in LCA

Two key pieces of quantitative information are required for the LCA practitioner to appropriately calculate the environmental burdens across recycling flows:

1. the collection rate
2. the metallic yield

As shown in Fig. 9, the collection rate (*W*) is a measure of the efficiency of the collection infrastructure and the

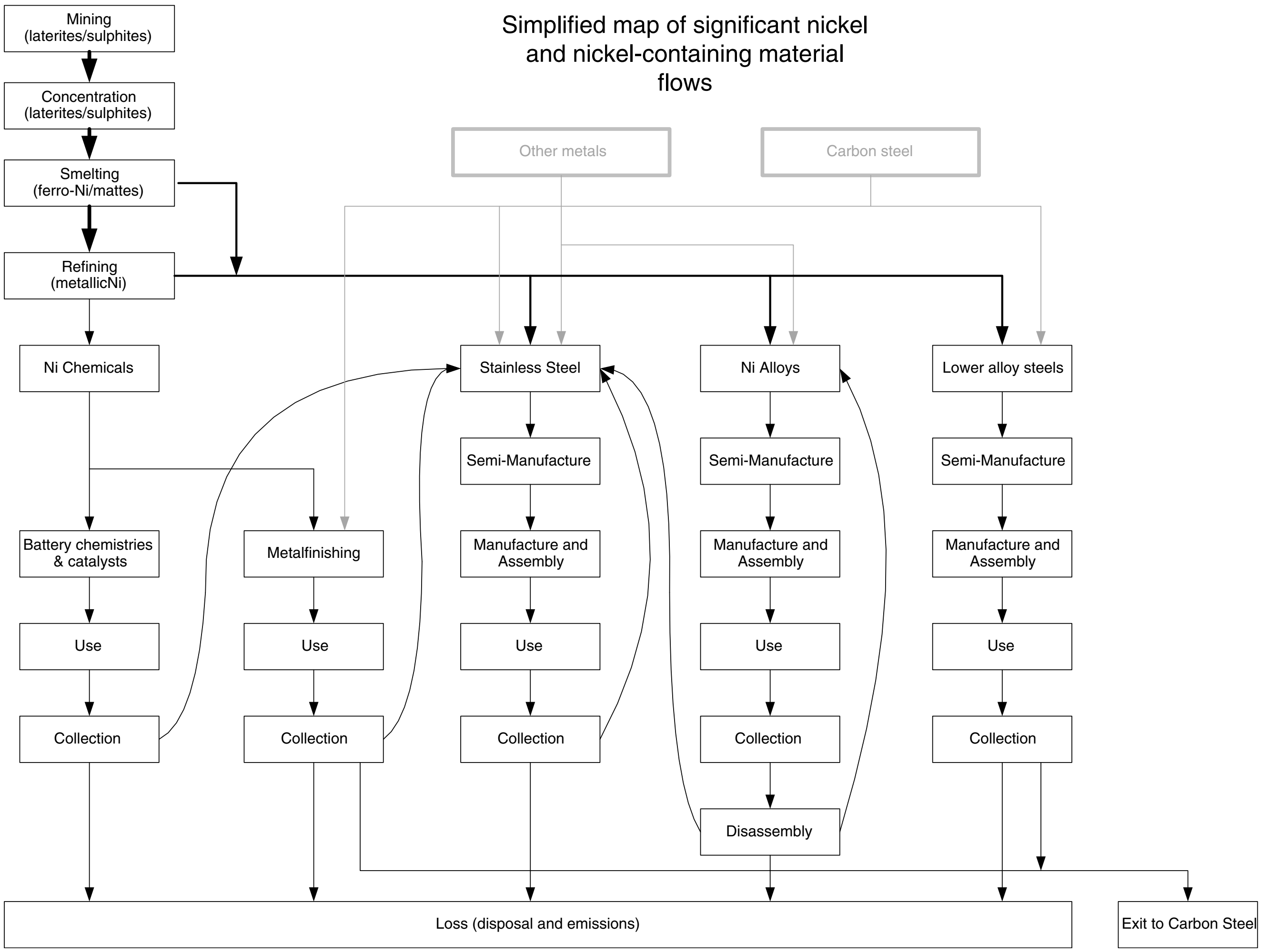


Fig. 7 Nickel—recycling map

metallic yield (Y) is a measure of the efficiency of the metallurgical process to reclaim a metal back to its desired quality. Most importantly, the product of the collection rate and the metallic yield (WY) is the quantification of the material loop and is referred to as "the recovery rate."

Collection rate More specifically, the collection rate (W) is the ratio of material that is recovered from the product after collection and disassembly, divided by the amount of material that entered the use phase.

$$W = \frac{\text{Material recovered after collection and disassembly}}{\text{Material entered at use phase}}$$

Over the useful life of a product, the metal of interest may be lost directly from use, for example as wear, erosion, and corrosion or as direct disposal to a landfill. There is also a loss of material resulting from collection and disassembly where, for example, contaminated material is removed and disposed of. W is a number less than 1 and represents the fraction of metal ultimately recovered for recycling.

W depends on product collection and disassembly and may vary significantly by geography because of variations in product density per unit of area, labor economics, and collections systems.

Metallic yield ratio The metallic recycling yield (Y) indicates the efficiency of the metallurgical process in converting scrap metal input to product, where:

$$Y = \frac{\text{Recycled material recovered after fabrication}}{\text{Material recovered after collection and disassembly}}$$

The metallic yield ratio, Y, also a number less than 1, is process and scrap type specific and needs to be determined and published for each commodity metal type. Scrap type indicates the level of contamination and the ratio of volume to surface area, which affects oxidation of metal and thus achievable yield. There will be different Y factors for different alloys and even for the same metal because there are numerous different recycling flows that depend on grade, technology, geography, and economic conditions.

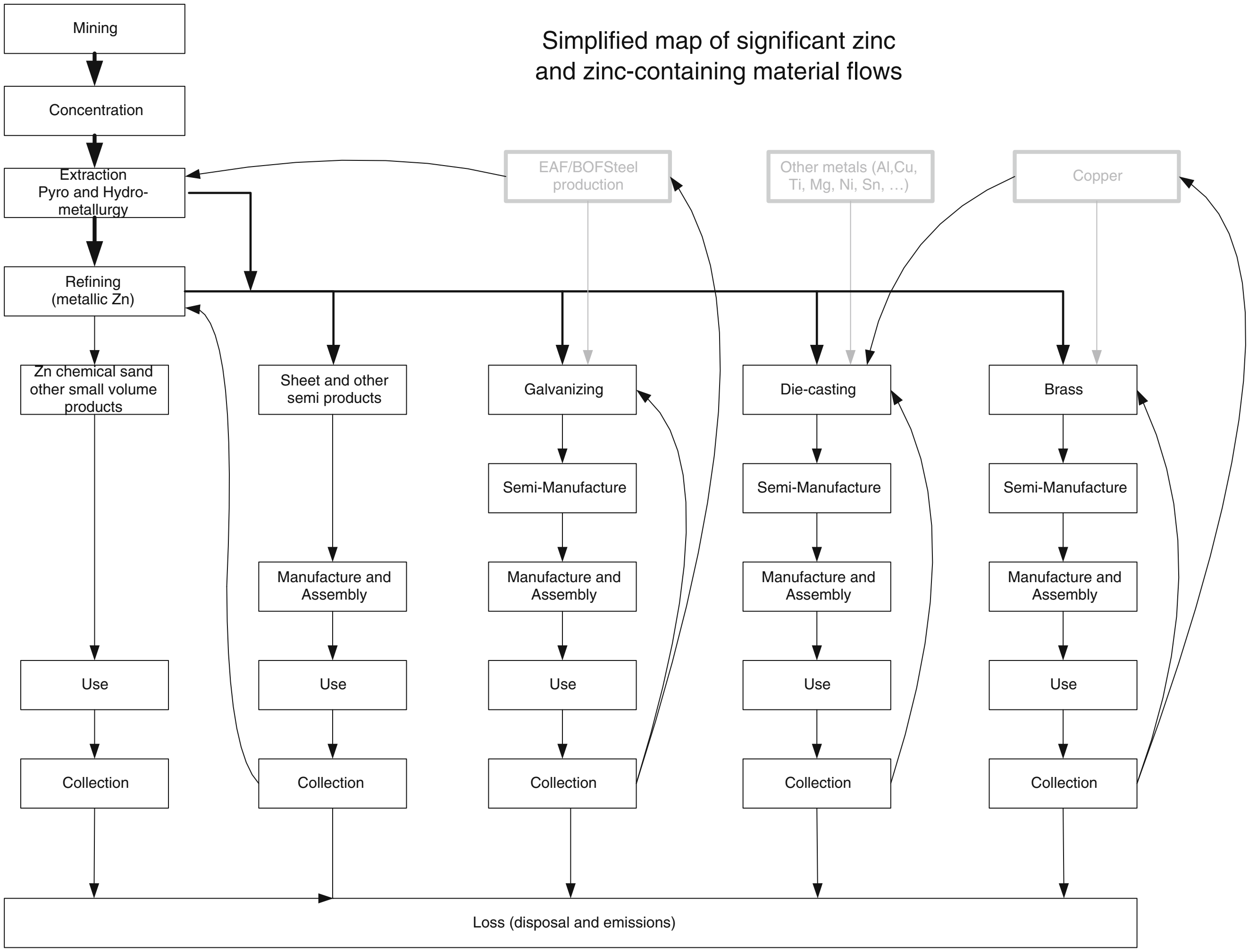


Fig. 8 Zinc—recycling map

Arithmetically it follows that:

$$WY = \frac{Recycled\ material\ recovered\ after\ fabrication}{Material\ entered\ at\ use\ phase}$$

Conceptually, WY is the yield of recycled material that remains in the material loop after recycling. In essence, the value WY is the measure of the ratio of material that completes one recycling loop, that is, a quantity of "WY" metal that is maintained in the economy.

3.8 Calculating environmental burdens according to ISO

The life cycle assessment standard, ISO 14044 (2006), supports two methods that can be used to determine the impacts of recycling metals:

Method a: Allocation between the primary production and the recycled products
Method b: Open-loop scenario with closed loop recycling procedure

Section 4.3.4.3.4 of ISO 14044 (2006) provides guidance on allocation between the primary production and the recycled products based on consideration of the number of subsequent uses.

Section 4.3.4.3.3 of ISO 14044 (2006) provides guidance on allocation of recycling products based on a procedure that applies a closed-loop method to an open loop, on the premise that inherent properties are preserved during recycling.

Both methods result in the same calculation procedure to determine the environmental burdens of a metal that is recycled. In general it involves a summation of the burdens associated with the amount of primary metal (including production and end-of-life burdens) to compensate for materials lost over the total life cycle of the material (a factor of $(1-WY)$), plus the impact of recycling activities as a factor of the recovery rate ratio (WY). See ISO 14049 (2000) sections 8.3.3 and 8.3.2, respectively, for (a) allocation between the primary production and the recycled products and (b) open-loop with closed loop recycling procedure.

Table 1 Metal recycling loop type examples

Type 1 Closed metal loop	Type 2 Alloy loop	Type 3 Transfer to another metal pool	Type 4 Metallurgical re-separation
Steel scrap is recycled by a minimill where it is remelted and formed into semi-products.	Stainless steel alloys are retained in a distinct metal pool. Constituents include iron, chromium, nickel and other elements.	Nickel in low-alloy steel is recycled into the steel loop, where it is retained in dilute fractions in the steel pool.	Gold and platinum group metals are retained in copper-rich metallic fractions during electronic equipment recycling. At the copper smelter, these other metals are separated and refined.
Steel scrap is recycled by an integrated mill where the recycled metal is blended with primary metal coming from the blast furnace into the basic oxygen furnace	Aluminum–magnesium alloy used for beverage cans is recycled as a distinct pool. The purity and properties of the alloy are managed and preserved.	Chromium coating on steel is recycled into the steel loop, where it is retained in dilute fractions in the steel pool.	Zinc used for galvanizing follows the steel onto which it is coated. During steel recycling, zinc is separated to electric arc furnace dust, which is treated to remove cadmium. Zinc is then recovered in an Imperial Smelting Furnace.
Copper in applications where it is nearly pure is recycled back to semi-fabricators, where it is remelted and reformed into semi-products	Brass is a copper-zinc alloy that is collected and recycled to retain alloy properties.	Due to inefficiencies in physical separation, Copper particles are entrained with the steel recycling flow. Once melted, copper cannot be removed economically from the steel.	

4 Results and discussion

Four metals recycling map models were generated based on a survey and analysis of current metals flow analysis. The value of the four recycling maps was demonstrated by applying them to three complex non-ferrous metals recycling loops. The utility of the recycling maps is to serve the basis of a structured approach to recycling allocation in life cycle assessment.

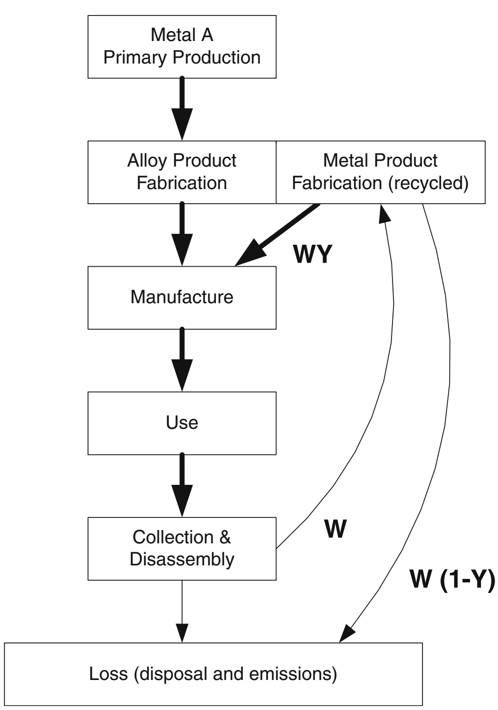


Fig. 9 Depiction of *W* and *Y* values

In addition to conserving quantities of metals in the economy, metal recycling serves to preserve useful material properties as well. Inherent properties include the physical, chemical, and electrical functionality of the material. For metal, these properties are predetermined by the elemental composition of the material itself.

In the patterns shown above for Types 1, 2, and 4 metals recycling, the quality of a metal is preserved as it goes through the phases of its life cycle. For Type 3, metal A can be effectively lost by dilution. The key question is: are we willing to add primary metal A to metal B? If the answer is no, metal A is effectively lost. For example, zinc that is combined with copper to form the alloy brass can be described by Type 2 recycling map, *closed alloy loop*. Once zinc and copper enter the brass metal loop, recycling of zinc and copper occurs within the brass metal pool without exiting to other metal pools, thereby preserving the desired quality of the economically viable and useful alloy, brass.

In a more complex scenario, such as in the case of Type 4 recycling, where metals are transferred and recovered from a separate metal pool, zinc follows a steel loop onto which it is coated, known as galvanizing, for the purpose of corrosion protection. During steel recycling, zinc is separated from the steel to electric arc furnace dust, which is

then treated to remove cadmium. The zinc dust is recovered in an Imperial Smelting Furnace and reenters the general zinc metal pool, likely to be used again for galvanizing of steel.

Although it is metallurgically possible, it is sometimes not economical to maintain exactly the same material properties after metal recycling. This depends on metal reactivity and other variables. In fact, it may be that the cost and environmental emissions are greater for a Type 1 recycling scenario than for primary production. In this situation, it may not be appropriate to process materials through a closed material recycling route, given that more suitable sources are available. Instead, this metal may be recycled into a Type 2 closed material recycling route (different metal pool), where its utility can be more economically realized.

5 Conclusions

A consensus on mapping metals is important in order to achieve an accurate understanding and measurement of metals recycling. To this end, consensus mapping, presentation of a general allocation approach, and identification of harmonized metrics were achieved among representatives of ferrous and non-ferrous metals groups.

6 Perspectives

Harmonized mapping, allocation procedures, and metrics on are only the start. Important work needs to be done to achieve accurate allocation factors based on sound empirical data to empower the various stakeholders—industry, policy makers, non-governmental organizations, and academics to make appropriate decisions based on agreed scientific bases. Examples include the continuing work of the Recycling Project Team (RPT)[1] (unpublished paper, 2006) and quantitative systems modeling approaches such as Markov chain modeling presented by Yamada et al. (2006), Matsuno et al. (2007), and Kirchain and Cosquer (2007).

[1] The RPT was comprised of the International Metal Study Groups (the International Lead and Zinc Study Group, the International Copper Study Group, and the International Nickel Study Group), Eurometaux, and Eurofer. Other organizations that participated in the work of the RPT were the Lead Development Association International, The International Zinc Association-Europe, the Nickel Institute, the European Copper Institute, the European Aluminium Association, and the Organisation of European Aluminium Refiners and Remelters, and the ICMM.

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